Chandrayaan-2 Onboard Results for Lander Horizontal Velocity Camera and Improvement for Chandrayaan-3

Tanisha Bhatia
Indian Space Reasearch organization
Bengaluru, India
tanisha_bhatia@leos.gov.in

Amit Maji
Indian Space Reasearch organization
Bengaluru, India
amit@leos.gov.in

Jayanta Laha
Indian Space Reasearch organization
Bengaluru, India
jayantalaha@leos.gov.in

Priyabrata Senapati
Indian Space Reasearch organization
Bengaluru, India
psenapati@leos.gov.in

Y Vijaya
Indian Space Reasearch organization
Bengaluru, India
yvijaya@leos.gov.in

2024 IEEE Space, Aerospace and Defence Conference (SPACE) | 979-8-3503-6738-6/24/$31.00 ©2024 IEEE | DOI: 10.1109/SPACE63117.2024.10668149

***Abstract*—This paper presents the on-orbit performance results of Lander Horizontal velocity camera (LHVC) obtained in Chandrayaan-2(CH-2) and the improvements carried out for Chandrayaan-3 (CH-3). LHVC computes velocity of Lander while descending by comparing two images using phase correlation image registration algorithm. LHVC was operated in various orbits and at various sun angles with respect to moon and the robustness of the sensor is seen in the results. Based on the Lander dynamics observed in CH-2, improvements are carried out in LHVC for minimum velocity measurement and rotation angle tolerance. The improvements are tested and the results are also presented.**

Keywords— FPGA, Flash, Phase Correlation, Exposure, dead band

I. Introduction

Chandrayaan-2 mission is India's first landing mission on moon which comprises of Orbiter, Lander and Rover. Orbiter is mainly used for Earth orbit raising, injection into Moon’s gravity and then orbit reduction of composite module(Orbiter +Lander + Rover) to 120km x 120km orbit. Post Orbiter-Lander separation, Lander engine is used for deboosting to 100km x 30km orbit. Laser Altimeter and LHVC from Laboratory for Electro-Optics Systems (LEOS) are developed as Navigational sensors to measure the Range and Horizontal velocity respectively which are used for updating navigation from 30km to touchdown.

LHVC sensor is a vision based navigation system used to measure the horizontal velocity of the lander. The sensor gives pixel shift in x and y direction (2D detector array axes) in real time which when combined with altitude and angular rate information gives velocity. The sensor consists of camera(Single image sensor-1024x1024) and processing electronics. The basic principle is - to acquire two images at Δt time interval, and find the corresponding pixel shift by image processing [1]. The basic Phase correlation algorithm is improved by image pre-processing and sub pixel interpolation so as to work in presence of noise [2-4]. The complete digital signal processing is done in a single FPGA to reduce mass, volume and power. Sensor is designed to operate from 7.5 km with 1Hz update and interfaced to Navigation, Guidance and Control(NGC) system through MIL-STD-1553. LHVC also has feature to store images in a Flash memory(SD card) which can be downloaded anytime through Base Band Handling (BDH) system to study the dynamics of landing [5][6]. Also, it has auto exposure feature which enables LHVC to operate from 2° to 60° sun elevation angle and terrains with different slope.

The paper is organized as follows: Section II gives the results obtained on board in Chandrayaan-2. Section III covers the improvements carried out in Chandrayaan-3. The test results for improved LHVC are presented in section IV. Finally, the inference drawn from the work done and future scope of work is discussed in section V.

II. Onboard results in Chandrayaan-2 (CH-2)

LHVC is operated at various times during CH-2. Planned range of operation of LHVC during landing is 7.5km to 100m altitude. However, it is operated at heights higher than 10km to assess the performance and also to capture images and verify the auto exposure performance of the sensor.

A. Performance in Intermediate Lunar orbit

LHVC is tested in Moon’s orbit with altitude of spacecraft as 4400 km and orbital speed of 0.6km/s. LHVC is operated for 350 seconds and continuous images are saved into flash memory which are later downloaded through BDH. Reference velocity of spacecraft is obtained from Orbit determination technique on ground. LHVC computes pixel shift between two images which are separated by 296ms time interval. Thus minimum velocity which is detectable at 4400km orbit for 296ms is 2.47km/s (minimum 1 pixel shift should occur between two images) therefore pixel shift value could not be achieved on-board. But as 700 images are captured in 350 seconds of operation, the images which are separated by 9.2 seconds are fed into LHVC algorithm in ground and pixel shift output in x & y axis is obtained. Fig. 1 shows two images captured during this test with time gap of 9.2sec. The default setting of LHVC for exposure is 2ms corresponding to 6° sun angle of

Authorized licensed use limited to: KIIT University. Downloaded on October 02,2024 at 11:22:45 UTC from IEEE Xplore. Restrictions apply.

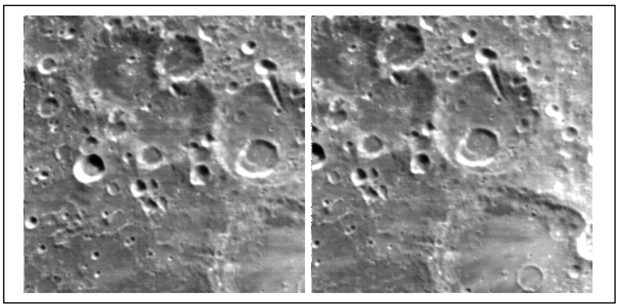

Fig. 1. Moon images captured by LHVC at 4400km height with a resolution of 715m

Landing day whereas sun elevation angle for this orbit is 30°, with auto exposure feature the new exposure value achieved is 0.5ms which has given images with required brightness and contrast.

Pixel shift obtained from LHVC is shown in Fig. 2 (X axis - Along the motion pixel shift) and Fig. 3 (Y axis – Across the motion pixel shift) respectively. Spacecraft velocity vector had component in both axes of LHVC. Pixel shift is combined with range and angle information to derive velocity. Total pixel shift corresponding to 0.599km/s at 4400 km is 7.51 pixel with image time separation of 9.2sec. Pixel shift obtained from LHVC is 7.23 and 1.19 pixel in X and Y axis respectively which corresponds to total pixel shift value of 7.32 pixel. Total velocity of 0.584 km/sec at 4400km is measured by LHVC against reference velocity of 0.599km/s. Error of 0.0152km/sec is observed. The accuracy specification of LHVC for 4400km is 0.0159 km/s, which is matching well with the computed velocity accuracy.

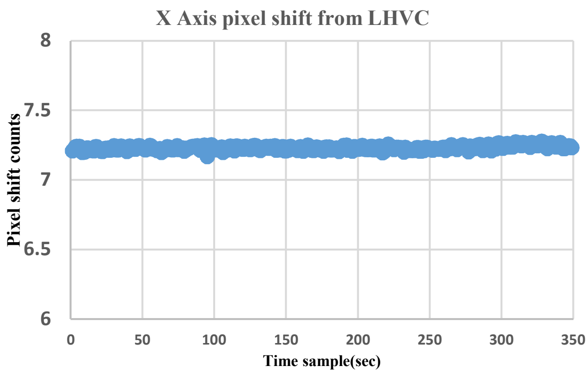

Fig. 2. X axis pixel shift From LHVC at 4400km height

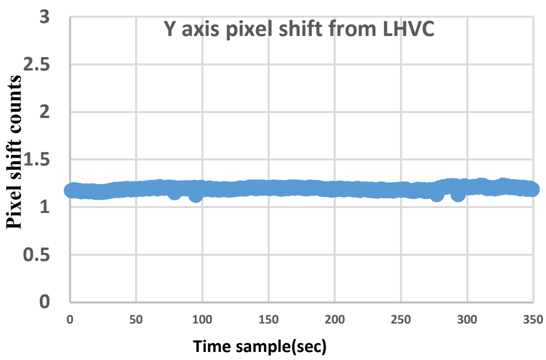

Fig. 3. Y axis pixel shift From LHVC at 4400km height

B. *During Landing (30km to 5.5km)*

VIKRAM, Lander of CH-2 power descent started from 30km altitude with initial velocity of 1.6km/s, LHVC started providing Lander velocity from 30km onwards and the last data of LHVC was obtained at 5.5km, few seconds before communication stopped from lander. LHVC data was compared with Inertial system: LIRAP (Laser Inertial Referencing and Accelerometer package). Fig.4 shows the velocity comparison of LHVC and LIRAP during landing and Fig.5 shows time vs altitude plot.

III. IMPROVED LHVC FOR CHANDRAYAAN-3

During CH-2 operations, LHVC operation in 4400km orbit and during landing gave insight to the performance of the sensor. The maximum angle anticipated on-board CH-2 , about LHVC optical axis during landing was 0.3° but in certain phases of descent, angles as high as 2° was observed which was out of LHVC measuring capability. In Fig. 4, it can be seen that LHVC velocity update at nearly 440 secs is wrong. It was observed that the angles experienced by LHVC was more than 2° at that time and as soon as angles came within LHVC limit, the velocity output became normal. Thus, there is a need to enhance LHVC angle tolerance. Also, one pixel was the least measurable (dead band) pixel shift as observed in 4400km orbit test. In Chandrayaan-3, LHVC is planned to be used at 150m altitude during hovering where horizontal velocity will be close to 0.01 m/s which is only 0.12-pixel movement between two images. Thus, improvement is done in computing sub pixel value when shift is less than 1 pixel.

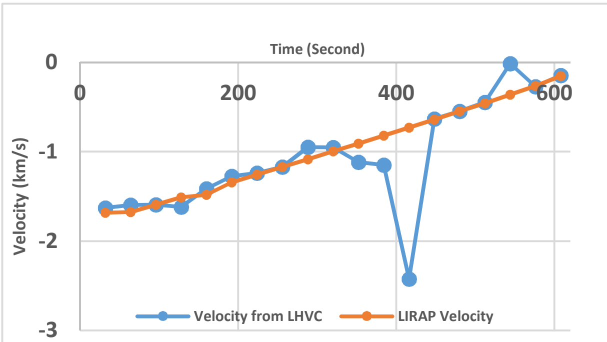

Fig. 4. LHVC Velocity vs LIRAP velocity during Landing from deboost start, CH-2

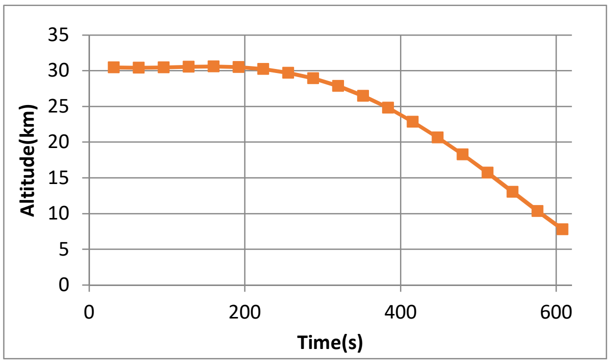

Fig. 5. Lander Altitude with time from start of deboost phase, CH-2

Authorized licensed use limited to: KIIT University. Downloaded on October 02,2024 at 11:22:45 UTC from IEEE Xplore. Restrictions apply.

A. Improvement in rotation angle tolerance

Rotation about boresight or optical axis of camera leads to image skewing and if such two consecutive images are compared, pixel shift is observed in both X and Y axis even in absence of actual translation motion. Using Log-Polar transformation method amount of rotation can be derived from images [7] but it is time consuming and requires additional FPGA resources. As LHVC requires to give real time updates, a simpler yet effective solution is used. Rotation angle between two images is taken as input from LIRAP and second image is corrected against 1st image for any planar rotation by implementing 2D rotation matrix as given in (1) before computing Image FFT and correlation.

$$\begin{matrix} x' \\ y' \end{matrix} = \begin{pmatrix} cos\Delta\theta B & -sin\Delta\theta B \\ sin\Delta\theta B & cos\Delta\theta B \end{pmatrix} \begin{matrix} x \\ y \end{matrix} \qquad (1)$$

where:

x = X axis pixel no

y = Y axis Pixel no

ΔΘB = Change in boresight angle between image 1 and 2.

Fig. 6 shows two consecutive images and impact of rotation on pixel shift output. Image 1 and image 2 are reference images with known shift of -1.798 pixel in X direction and 17.2-pixel shift in Y direction and in plane rotation of 10 degrees. Both the images are fed into two algorithms: 1) Without rotation correction and 2) with rotation correction (angle as Input from LIRAP). Results obtained from both methods are shown in Table I. The errors are huge in case 1 and error is within 0.15 pixel after rotation correction, i.e. second method. With this method, the rotation angle tolerance has increased from 0.5° to 10°.

B. Dead Band reduction

LHVC uses sub-pixel interpolation to compute pixel shift output with accuracy of 0.2 pixel. Sub-pixel interpolation is implemented on point spread function(PSF) of IFFT peak which is usually spread on 3x3 pixel with the

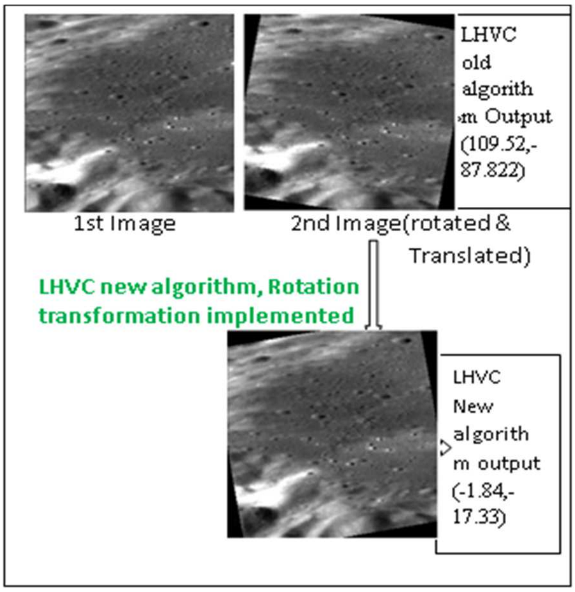

Fig. 6. Impact of Boresight rotation angle correction

TABLE I. LHVC RESULTS WITH AND WITHOUT ROTATION CORRECTION

LHVC output	X Pixel shift	Y Pixel shift	Error in X pixel shift	Error in Y pixel shift
Without rotation Correction	109.52	-87.822	111.318	105.022
With rotation correction	**-1.84**	**17.33**	**0.04**	**0.13**

center pixel as the maximum value. For CH-2, if the IFFT peak is present at pixel (0,0), values at pixel (0,0), (1,0), (0,1) and (1,1) were used for sub pixel calculation which lead to accuracy of nearly 1 pixel. Thus minimum velocity that could be measured was limited to one pixel. For CH-3, analysis of IFFT peak is done and it is observed that when IFFT peak lies on (0,0) pixel than the PSF is spread at pixels (0,0), (1,0), (0,1), (1,1), (255,0) & (255,255) for image size of 256x256 pixel. Fig. 7 shows the presence of side lobes at pixel (255,255) and (255,0) when IFFT peak is present at pixel (0,0). With this accuracy of 0.2 pixel can be achieved at image origin or even at any corners or with velocity in only one axis. Table II shows the improved parameters of LHVC from CH-2 to CH-3.

C. Fast readout to reduce vibration effects

LHVC uses STAR1000 CMOS detector which is a rolling shutter detector. Thus, bottom lines are being exposed when top lines are being read. Thus, it may cause smear in images if the velocity or jitter is high. Fig.8 shows one of the image captured by LHVC when the platform where LHVC is mounted is experiencing jitter. It transforms to variable movement in different rows thus distorting the image. The effect of this movement can be seen in IFFT of the two correlated images as shown in Fig. 9. Multiple peaks are present due to which actual shift cannot be detected. LHVC is capable of giving valid pixel shift output only when whole image experiences same motion (One single peak in IFFT).

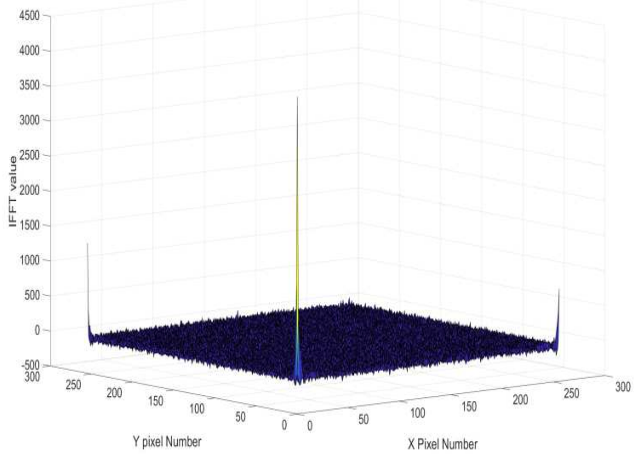

Fig. 7. PSF for IFFT peak at pixel (0,0)

Authorized licensed use limited to: KIIT University. Downloaded on October 02,2024 at 11:22:45 UTC from IEEE Xplore. Restrictions apply.

TABLE II. LHVC IMPROVED PARAMETERS

S.No	Parameter	Spec for CH-2	Spec for CH-3
1	Velocity (min)	5.4m/s@10km 0.05m/s@100 m	1.09m/s@10km 0.01m/s@100m
2	Maximum angle tolerance	0.5^0	10^0

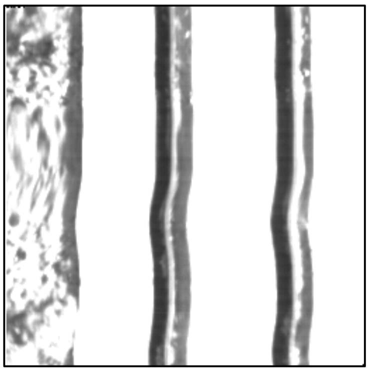

Fig. 8. LHVC image in presence of jitter

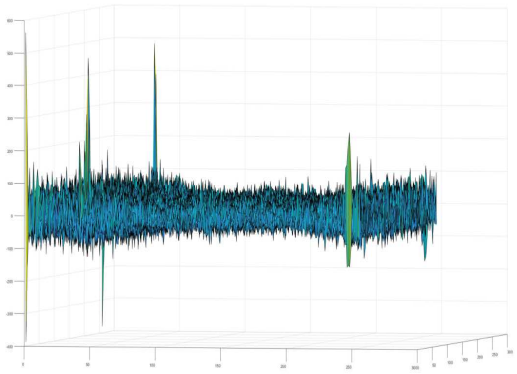

Fig. 9. Multiple peaks in IFFT of two correlated image

The read out time of LHVC was 23ms thus any jitters within this time (frequencies > 20Hz) will distort the images. Due to the rolling shutter property this effect cannot be completely nullified but is reduced by reducing the read out time to 7ms.This shifts the affecting frequency to 3 times (nearly 60Hz) but still the lower frequencies can affect based on the phase of the oscillation when image is being captured.

IV. TEST RESULTS

Many tests are carried out on CH-3 LHVC package to confirm the performance in presence of boresight rotation and also accuracy of sensor with almost zero velocity. Dynamic motion test is done on helicopter where LHVC is mounted such that it looks down from helicopter belly. This test confirms LHVC performance with velocity as well as angles. Velocity plot of LHVC against reference Inertial Measurement Unit (IMU- accuracy of 0.01m/s) at 150m altitude is shown in Fig. 10. Helicopter tests include LHVC, NGC and other sensors thus it is a complete end to end testing as will be in actual flight. Sensor is calibrated in a standalone test which demonstrates aaccuracy improvement. For standalone test, state of the art facility is used which has maximum altitude range of 120m and velocity capability of 0.01m/s to 4m/s. In this test, Sensor is mounted on a moving carriage whose velocity is controlled and known with accuracy of 0.001m/s. Fig.11 shows the plot for 0.01m/s carriage velocity where LHVC velocity is plotted against the Reference sensor. LHVC accuracy is measured as 0.0031m/s. Table III shows the result of calibration test at 120m range for different velocity tests. Accuracy achieved at 120m is extrapolated for estimating accuracy at 150m.

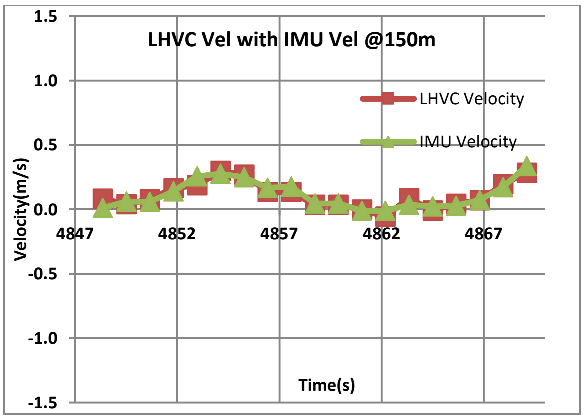

Fig. 10. LHVC Velocity compared with IMU velocity

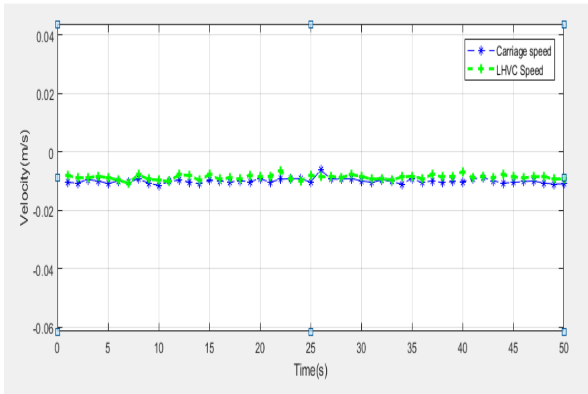

Fig. 11. LHVC velocity vs Reference sensor velocity

TABLE III. LHVC Calibration test

Speed of carriage(m/s)	3 sigma accuracy of LHVC(m/s))
0.6	0.01
0.4	0.0047
0.2	0.01
0.05	0.007
0.02	0.0063
0.01	0.0031

Authorized licensed use limited to: KIIT University. Downloaded on October 02,2024 at 11:22:45 UTC from IEEE Xplore. Restrictions apply.

V. Conclusion

A low mass and low power vision-based velocity sensor realized for CH-2 was tested at different phases and the design was verified and validated. Short comings and the lessons learnt from CH-2 and improvements have been done in terms of accuracy, dead band, boresight rotation angle tolerance & vibration effect in CH-3. All parameters are tested and demonstrated on ground. Also, LHVC has successfully updated horizontal velocity in CH-3 which led to soft landing of Lander.

Acknowledgment

The research work has been supported by Director, Laboratory for Electro-Optics Systems (LEOS)-ISRO, Dr K.V Sriram , Associate Director Mrs Kalpana Arvind, K.A.Lohar, DPD-LEOS Sensors, CH-3. We thank them for their valuable encouragement and guidance. Also, we would like to thank Dr. Koteshwar Rao and Shri J.A.Kamalakar who have reviewed the sensor thoroughly and helped in the improvement.

References

[1] C.D. Kuglin and D.C Hines, " The Phase correlation image alignment method", Proceeding in IEEE International Conference on Cybernatics and Society, New York,1975G.

[2] Tanisha Bhatia, Amit Maji, JayantaLaha, MM Mehra, "Practical approach for implementation of phase correlation-based image registration in FPGA" IEEE ICCTCT 2018, Coimbator J. Clerk Maxwell, A Treatise on Electricity and Magnetism, 3rd ed., vol. 2. Oxford: Clarendon, 1892, pp.68–73.

[3] Satbir Kaur and Ishpreet singh, "Comparison between Edge Detection Techniques", International Journal of Computer Applications, Vol 145-No.15, July 2016.

[4] Hassan Foroosh (Shekarforoush), Josiane B.Zerubia, "Extension of Phase Correlation to Subpixel Registration", IEEE transactions on Image Processing,Vol.11, No.3,March 2002.

[5] Tanisha Bhatia, Jayanta laha, Amit Maji, Arindam mal, K Subhalakshmi, "Design of FPGA based horizontal velocity computation and Image storage unit for Lunar Lander", IEEE UPCON 2017, Mathura.

[6] Tanisha Bhatia, amit Maji, jayanta Laha, m.M Mehra, H S Ravindra, Subhalakshmi K, "Lunar Lander Horizontal Velocity Computation Using Vision based Sensor for Chandrayaan-2" at Satellite Technology Day Symposium 2018, Bangalore and ISSN 0971-1600, Journal of Spacecraft Technology ,Vol. 29, No 1, pp 19-24, Jan - Jun 2018.

[7] Ruben Gonzalez, "Improving Phase Correlation for Image Registration", International Conference Image & Vision computing (IVCNZ), New Zealand 2011.

Authorized licensed use limited to: KIIT University. Downloaded on October 02,2024 at 11:22:45 UTC from IEEE Xplore. Restrictions apply.